Three and a Half Centuries Later – The Modern Art of Liquid-column Manometry

metrologia

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Abstract. After three and a half centuries the Torricellian mercury manometer remains the most accurate pressure standard. State-of-the-art manometers achieve parts-per-million total uncertainties near atmospheric pressures and imprecisions as low as 0,01 Pa. The total uncertainty is determined primarily by uncertainties in the measurement of the height of the mercury surfaces and the average mercury density. The latter is limited generally by the uncertainty of the average temperature of the mercury. The techniques used to locate the mercury surfaces and determine their heights not only determine the imprecision and accuracy of the height measurement, but can also have a significant effect on the maintenance of a stable and uniform mercury temperature. This review discusses the factors important in high-accuracy manometers with particular emphasis on surface detection and height measurement techniques. Specifically discussed are capacitance detection, white-light fringes, optical interferometry, with and without floats, and ultrasonic measurements.

1. Introduction

Evangelisti Torricelli's inversion of a liquid-filled tube to generate a vacuum was not unique – he was but one of a group centred on Galileo that was attempting to refute the accepted wisdom that "nature abhors a vacuum". Nor is it clear that he was the first to use mercury to fill the tube. However, he is generally credited with the discovery that the height of the mercury in the inverted tube could be used as a measure of atmospheric pressure. The importance of this discovery, which can be fairly called the beginning of pressure metrology, was soon evident; his "publication" in 1642 was quickly followed by a number of replications of his experiments, and the use of Torricellian barometers in important experiments commenced almost immediately, most notably with Blaise Pascal's demonstration that atmospheric pressure decreases with increasing elevation. The applications of pressure measurements greatly increased with the Industrial Revolution, and the variety of uses and demands for better accuracy have continued to grow ever since. It is remarkable that in spite of tremendous changes in technology, the Torricellian barometer remains today the most accurate type of pressure standard.

The applications, complexity, accuracy and cost of liquid-column manometers vary greatly. This review focuses on high-accuracy mercury manometers of the types currently used as national standards for pressures around atmospheric. The focus is on the relative advantages and disadvantages of the different types, with design details left to the references. A detailed analysis and comparison of uncertainties is not attempted, in part because the uncertainty analyses provided for different instruments are so varied in detail and plausibility. It should be noted that several of the instruments of interest are discussed in more detail elsewhere in these proceedings and other relevant reviews are available; an older review by Guildner and Terrien [1] discusses high-accuracy mercury manometers with an emphasis on the types developed in their laboratories, Ruthberg [2] reviews manometers for low-range absolute measurements, Peggs [3] discusses low-range differential or gauge measurements, and two recent reviews of pressure measurements by Pavese and Molinar [4] and Tilford [5] include extensive material on manometers.

The endurance of the Torricellian barometer is due in no small part to its simplicity; it is only necessary to measure the vertical displacement of a liquid of known density in a known gravitational field. This discussion

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treats each of these parameters in turn, with most of the attention focused on the determination of the vertical displacement.

2. Gravity

There is little to be said about gravity. Modern techniques [6] allow the determination of the absolute acceleration of gravity g, with a total uncertainty of parts in 10^9, far below the level that is of consequence for pressure measurements. Relative or transfer measurement techniques have an imprecision at about this same level and can be readily used to determine g at individual manometer sites. As a practical matter, most experimentalists choose not to correct for tidal effects and accept a residual uncertainty of 0,2 ppm to 0,3 ppm.*

3. Liquid Density

The persistence of the Torricellian manometer as the state-of-the-art pressure standard is due in no small part to the properties of mercury. Not only is mercury elemental and immutable, it is relatively inert and can be purified to the parts-per-billion level by treatment with potassium hydroxide and nitric acid solutions, followed by distillation (mercury cleaning procedures and other relevant material are reviewed in [7]). For manometry it is necessary to determine the absolute density, a difficult measurement that was carried out in a notable experiment by Cook [8]. Cook's stated uncertainty is somewhat ambiguous, but appears to be about 1/3 ppm to 1/2 ppm at the one standard deviation level. Cook's efforts have been supplemented by recent work at the former Amt für Standardisierung, Messwesen und Warenprüfung [9, 10]. This work has a better defined uncertainty, again about 1/2 ppm. However, the complexity of the absolute measurements limits them to a few samples and the possibility exists of significant sample-to-sample density variations; mercury has a varied isotopic composition, six isotopes each contributing between 7 % and 30 % of the natural abundance. Fortunately the density of individual samples can be compared with absolute reference samples with an imprecision of 0,01 ppm using a comparison technique developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO) [11]. Compared with other liquids, mercury has a relatively small thermal expansivity and compressibility; about $181 \times 10^{-6}\,K^{-1}$ and $4 \times 10^{-11}\,Pa^{-1}$, respectively, at room temperature and atmospheric pressure. The best thermal expansivity measurements still appear to be those of Beattie and co-workers [12] and low-pressure compressibility measurements are reviewed in [10]. Density and thermal expansivities, derived from these sources, are given in tabular and equation form for both the International Practical Temperature Scale of 1968 and the International Temperature Scale of 1990 in [5].

While the density of mercury at a specified temperature can be known at the 1 ppm level, temperature uncertainties can restrict the average density in an operating manometer to a much larger uncertainty, and this uncertainty is often the limiting factor in high-accuracy manometry. In spite of the fact that thermometers can be readily obtained with uncertainties at the 1 mK level, it may be difficult to determine the average temperature of the mercury due to spatial and temporal variations. Because of the thermal lag of the often large amounts of mercury used, and the difficulty in placing thermometers in direct thermal contact with the mercury, time must be allowed for the mercury to equilibrate with these variations. The extent of these variations depends on the laboratory environment, the design of the manometer, and how it is used. In particular, the type of length measurement technique used can, as discussed below, affect the type and extent of temperature control that may be used. Further, allowance must be made for the adiabatic heating and cooling effects that occur in the gas when the pressure is changed. To understand and minimize temperature and density uncertainties it is very desirable to use multiple thermometers to determine the extent of spatial variations and to reduce their effect by averaging. It is further desirable to monitor the time dependence of the measured temperature(s) before, during and after a measurement.

4. Vertical Displacement

Measurement of the vertical displacement of the mercury column requires determination of the vertical axis, location of the mercury surfaces and measurement of the distance between them along the vertical axis. Since errors due to deviations from the vertical vary as the cosine of the deviation, or as the square of the angular deviation, determination of the vertical with adequate precision is not difficult; a simple plumb bob or autocollimation of a light beam from the mercury surface will suffice. However, errors due to tilts, or changes in the orientation of the measurement axis during a measurement, vary as the sine of the change and the horizontal distance between mercury surfaces. Depending on the geometry of the manometer and the desired imprecision in the length measurement, this can require angular stabilities of the order of microradians and/or the use of three-column or W-tube designs, which include a tilt meter that compensates for small angular deviations [13].

Location of the surfaces is much more challenging, and different manometer designs are usually distin-

* 1 ppm ≡ 1×10^{-6}.

guished by the different techniques used to locate the surfaces and measure the distance between them. This discussion focuses on different surface detection and height measurement techniques, and their associated imprecisions and accuracies. But it should be kept in mind that detection and measurement techniques can have other significant effects on the overall accuracy and the utility of the manometer. As noted, it is necessary to maintain a uniform and stable temperature over the entire non-horizontal portion of the mercury columns. However, the surface detection and length measurement techniques can have a significant affect on the temperature stability; some techniques require servo systems or human intervention that can generate heat and/or restrict the design of temperature-stabilizing systems. Some techniques require sophisticated vibration isolation, which can also restrict or complicate temperature control and the use of the manometer, while others routinely operate in a normal laboratory environment. Some techniques allow the tracking of slowly changing pressures; others work only with fixed pressures. Some techniques are slow and require manual operation, others are readily adaptable to automatic data acquisition.

An additional factor determining the accuracy of measurement of the displaced height is the perturbation of the surface caused by surface tension or capillary effects. These effects can vary during the use of a manometer and are difficult to predict and correct. However, the magnitude of this effect can be readily trivialized with the use of large-diameter surfaces. For example, using Blaisdell's expressions for a sessile drop [14], a conservative estimate of 1 μm can be calculated for the maximum displacement of the centre of a mercury surface with a diameter of 35 mm. Larger diameters further decrease this limit; the displacement near the centre of the surface decreases rapidly with increasing diameter of the mercury surfaces so that for round tubes larger than 10 mm in diameter the maximum possible perturbation decreases by more than an order of magnitude for each 10 mm increase in diameter. If, as discussed below, a float is used, perturbations of the vertical position of the float depend on the distance between the outer diameter of the float and the walls of the manometer tube. These considerations all favour the use of large-diameter mercury surfaces.

The most common vertical displacement measurement techniques involve visual detection of the surfaces and comparison with an adjacent length scale. The detection can be aided by sighting rings, pointed probes and/or special lighting schemes. While such techniques have been widely used, their precision is operator dependent and limited to a few micrometres at the best, and they generally require unrestricted visual and mechanical access to the manometer, greatly complicating the temperature control problem. This discussion is confined to nonvisual techniques that have been developed for the most accurate instruments.

4.1 Capacitance detection

Direct electrical contact can be used to locate the mercury surface, but perturbations of the surface by the electrical probe limit this technique to an imprecision of about 5 μm. Much more successful is the capacitance technique used by Stimson [15]. Measurement of the capacitance between a horizontal plate and the mercury surface allows location of the mercury surface with an imprecision of a nanometer, or even less. The capacitor plate is included in the top of a large-diameter (of order 100 mm) cistern. The mercury in two or three such cisterns is coupled together with flexible tubing to form a U-tube or W-tube manometer. One of the cisterns is movable so that it can be elevated to balance the pressure applied to the other cistern(s) and to maintain the mercury at a constant distance from the capacitor plates. The use of the capacitance technique and the cisterns has two major advantages; the measurement of the mercury surface location is easily averaged over time and the area of the capacitor plate, greatly reducing the effects of vibrational disturbances. The use of large-diameter cisterns and small-diameter flexible tubing further allows the reduction of capillary effects to a negligible level while minimizing the amount of mercury required.

Determination of the pressure requires the measurement of the vertical displacement of the movable cistern. Stimson's original design evolved into an instrument (no longer in existence) used for gas thermometry at the National Bureau of Standards, which supported the movable cistern on a stack of gauge blocks [16], allowing a high-accuracy measurement of the vertical displacement. The stated total uncertainty of the instrument for a pressure of 100 kPa was 2 ppm. However, attainment of this level of accuracy required a special temperature-controlled room, and temperature control was significantly complicated by the necessity to manually generate a new stack of gauge blocks each time the pressure was changed; typically, 18 hours was required before stability was achieved following a pressure change. The cistern and capacitance technique was also used in a manometer constructed at the D. I. Mendeleyev Institute for Metrology, but in this case a line scale was used to measure the height of the movable cistern [17].

The cistern and capacitance technique has been successfully applied in a series of commercial manometers that are widely used for high-accuracy industrial calibrations. These instruments elevate the movable cistern on a precision lead screw; the elevation of the cistern is measured by the rotation of the lead screw or, in later versions of this design, by a laser interferometer employing a retroreflector attached to the movable cistern. These instruments are automated and can track changing pressures. Their accuracy is generally stated to be about 30 ppm (probably at the 3 σ level) and is primarily limited by temperature uncertainties. At least two national laboratories, the Institut National de Métrologie (INM) and the Physikalisch-Technische Bundesanstalt (PTB) have achieved 1 σ uncertainties as small as 2,5 ppm by modifying commercial instruments of this type [18-20], principally by relocating heat-generating electronics and servo systems, and improving the temperature control and measurement. Not surprisingly, these improvements of temperature control and pressure measurement accuracy are obtained at the expense of flexibility of operation; the best performance of the PTB manometer can be obtained only with decreasing pressures for which the cistern elevation mechanism can be turned off.

The capacitance sensing technique has also been applied to a manometer with a range of 120 kPa by the former Ceskoslovensky Metrologicky Ustav [21, 22]. The outer of two concentric tubes serves as the reference or low-pressure side of the manometer, while pressure is applied to the mercury in the centre tube. The mercury in the outer tube is maintained at a fixed distance from a capacitive sensor at the top of the tube by varying the volume of a mercury reservoir attached to the bottom of the manometer. The mercury surface in the centre tube is detected and tracked by a manually-adjusted capacitive probe that moves along the vertical axis. The movement of the probe is measured with a laser interferometer, using a cube-corner retroreflector attached to the probe. The manometer is mounted on a vibration-isolated base and enclosed in a water bath. It achieves an imprecision of 0,07 Pa, and a stated total uncertainty at 100 kPa of 1,8 ppm. Operation is restricted by the necessity to manually adjust the probe tracking the centre column.

4.2 Optical detection and measurement

The obvious solution to the surface detection and length measurement problem is optical interferometry, with the mercury surfaces used as mirrors in an interferometer illuminated by a laser. Unfortunately, this solution is immensely complicated by the low viscosity of mercury and the consequent instability of the surfaces. Even with good vibration isolation the residual disturbances on the surface of a deep mercury pool have amplitudes of about a micrometre and wavelengths of the order of millimetres to centimetres. Since the detected interferometer signal is a spatial average over the area of the interferometer beams, it represents the average of the phase or intensity of the interference signal over the disturbed surface. If large-diameter interferometer beams (greater than a small fraction of the disturbance wavelength) are used, and the amplitude of the disturbance is comparable to one half the laser wavelength, the spatial average approaches the mean of the minimum and maximum amplitude fringe signals, and the signal variations due to overall height changes of the column become a decreasingly small fraction of the average signal, i.e. the fringe pattern averaged over the optical beam becomes an undistinguished "grey", and little or no change in the fringe signal is detected as the mercury column changes height. Small-diameter beams minimize this problem, but the local tilting of the mercury surface that occurs when a disturbance passes causes an angular deviation of the reflected beam that destroys the overlap and the interference of the beams. The problem is further complicated by much larger amplitude transient disturbances that can be generated when the pressure is changed and the mercury surface moves up and down in its containment. This makes it particularly difficult to use fringe counting to keep track of the changing height when the pressure is changed. Because of the difficulties with this "obvious" solution, several other optical techniques have been developed to detect the mercury surfaces and measure the displacements.

4.2.1 White-light fringes

Terrien [23] discussed several optical techniques for locating a mercury surface, including white-light fringes. When a Michelson interferometer is illuminated with broadband light (white light) a fringe can be detected only when the optical path lengths of the two arms of the interferometer are equal, or very near to equal. If one arm of the interferometer includes a mercury surface as the reflecting mirror, the location of the mercury surface can be tracked by moving the mirror in the second arm to maintain the white-light fringe. The change in height of the mercury surface can be determined from the displacement of the movable mirror.

Several manometers have been constructed using the white-light technique. The National Research Laboratory of Metrology (NRLM) uses this technique in a mercury manometer with a range of 120 kPa [24]. The locations of the mercury surfaces are detected with an imprecision of 0,4 µm to 0,7 µm, depending on the time of day and the vibration level. The displacement of the mercury surfaces is determined by measuring the displacement of a movable mirror along a line scale. The temperature of the mercury is stabilized by enclosing the manometer in a temperature-regulated water bath. The combined standard deviation of all error sources was estimated to be between 0,16 Pa and 0,32 Pa, depending on operating conditions. A white-light interferometer manometer constructed at the Bureau International des Poids et Mesures, with a range of 100 kPa, also uses a line scale to measure the displacement of the movable mirror [25]. This manometer uses aluminum heat shields to maintain temperature uniformity and a damped spring suspension to minimize vibrations. It achieves an uncertainty of a "few times" 0,1 Pa. This instrument has been commercially replicated and is used in several other laboratories.

The use of a line scale to measure the displacement of the movable mirror requires manual operation and can limit the precision and accuracy of the length measurement. A short-range (13 kPa) white-light instrument at the NRLM uses a fringe-counting laser interferometer to measure the displacement of the movable mirror [26]. A laser interferometer is also used in a 100 kPa range manometer at the Institute of Physical and Radio Technical Measurements, Moscow [27]. This instrument is supported by tennis balls, inner tubes and a chain to minimize vibrations, and uses a double set of concentric-tube manometers so that the centre of gravity of the mercury does not shift with changing pressures and cause the manometer to tilt.

Optical-interferometer measurements, whether used to locate a surface or measure a displacement, must be corrected for the index of refraction of the gas through which the light beams propagate. This correction can be especially large for white-light instruments since corrections must be made not only for the optical path in the manometer, where the gas is generally of high purity and has a well-known pressure and temperature, but also for the gas in which the movable mirror operates, which is generally air. Depending on the pressure, gas and mode of operation (absolute or differential), this correction can be as large as 0,1 %. This problem has been reduced in a new manometer at the NRLM in which the entire interferometry system, including the movable mirror, is located in a sealed enclosure filled with the pressurizing gas [28]. This instrument uses a laser interferometer to measure the displacement of the movable mirrors and a total uncertainty of 0,4 Pa is estimated at 100 kPa.

4.2.2 Float retroreflectors

Another "obvious" way to use optical interferometry is to float retroreflectors on the mercury surfaces, and so reduce or eliminate the effects of mercury-surface disturbances. A further advantage is that floats automatically follow the mercury surface as the level is changed, without the aid of a servo system, permitting the measurement of changing pressures. However, floats can be maintained in the centre of the surface only by a mechanical constraint. Even with low-friction contacts, the combination of residual frictional and capillary forces can cause significant variations in the height of the float with respect to the mercury surface. Two different approaches have been taken to minimize this problem.

A float retroreflector developed by Bennett et al. [29] uses a cat's-eye retroreflector, with the optical beam focused to a point on the mercury surface by a lens supported on a float. This minimizes the effects of disturbances in two ways: the diameter of the optical beam at the mercury surface is very small compared to the wavelength of the disturbances on the mercury surface, so the variation of intensity across the interference pattern is much less than one fringe. The focusing lens has the further effect of reducing the angular deviation of the reflected beam, so that a useful overlap of the incident and reflected beams can be maintained over a long distance. The float can be designed to minimize disturbances on the reflecting surface by using a shallow (several millimetres deep) pool of mercury inside the float, which communicates through a small hole with the mercury in the manometer tube proper. The surface-wave energy in a shallow pool is dissipated much faster than in a deep pool. Using these techniques the signal perturbations due to disturbances on the mercury surfaces are minimized to a level that not only allows continuous tracking of pressure changes, but also permits fringe counting at relatively rapid rates (equivalent to mercury level changes of 1 mm/s) during the pressurization of a manometer. However, changes in the height of the float and the lens relative to the mercury surface, caused by capillary effects, cause the reflected beam to have a curved wave front. When this interferes with the original plane wave front, it causes a second-order perturbation of the measured height, the magnitude of which depends on the optics of the cat's-eye and the change in the relative height of the lens.

The cat's-eye type of float is used in a manometer at the National Physical Laboratory (NPL) with a range of 110 kPa. It has also been used at the CSIRO in a manometer with a range of 100 kPa [30]. The CSIRO floats have the added feature that the wall of the float at the interface with the reflecting mercury surface is inclined at the "normal" mercury contact angle, with the intention of minimizing capillary effects on the height of the enclosed pool of mercury. Both the NPL and the CSIRO floats are centred by low-friction contacts with the wall of the manometer tube. The NPL instrument employs a water bath to maintain a constant temperature. It achieves an imprecision of 0,3 μm and has an overall 1 σ uncertainty in the pressure at full range of 1,6 ppm. The CSIRO instrument includes a pneumatic antivibration support, a metallic thermal shield and an air bath for temperature control. The published uncertainty analysis, which appears to be preliminary, lists a length imprecision of 0,1 μm, and lists temperature gradients and instabilities as the major contributor to a total 1-σ pressure uncertainty of 2 ppm at full range.

Two new manometers developed at the Istituto di Metrologia "G. Colonnetti" (IMGC), with ranges of 120 kPa, use floats with cube-corner retroreflectors contained in 50 mm diameter glass tubes [31]. These floats are also centred by low-friction contact with the tube wall. Capillary effects are minimized by the use of lightweight floats which minimize the perturbation of the surface and the use of a mercury injector to raise the level of both columns before a measurement. This takes advantage of the fact that the contact angle, shape and depression are much more reproducible for a rising surface than for a falling surface. This adjustment of the surface height presumably makes it difficult to follow changing pressures, but does help to achieve an imprecision in the height measurement of better than 1 μm. Temperature is stabilized by a water bath at the level of 10 mK, and preliminary estimates indicate an overall 1-σ uncertainty of better than 5 ppm at 100 kPa.

Floats with cube-corner retroreflectors are also used in a 100 kPa range manometer at the National Institute of Metrology in Beijing [32]. The floats in this case are restrained in the centre of the surface by sapphire bearings that ride along stainless steel wires stretched vertically through the mercury. The heights of the floats are tracked both by fringe counting and white-light interferometry, which serves to check the accuracy of the fringe count. The floats contact the mercury surface with a sloping surface designed to minimize capillary effects. The manometer is contained in a temperature-controlled oil bath. An imprecision of 0,04 Pa is achieved and a total 1 σ uncertainty of better than 1 ppm is claimed at 100 kPa.

4.2.3 Interferometry – bare mercury surface

The advantages of optical interferometry following direct reflection from a mercury surface can be realized if the wavelength of the interferometer illumination is long compared to the amplitude of the surface disturbances. Tilford demonstrated that this could be done using the 10,6 µm radiation from a carbon dioxide laser [33]. With the manometer isolated from horizontal vibrations by suspending it from a chain, the fringe signal was stable enough to permit fringe counting for low rates of movement of the mercury surfaces. A carbon dioxide laser has the further advantage that the wavelengths are known to one part in 10^9. The carbon dioxide laser interferometer was not fully developed into a working manometer. However, it was used for the determination of the speed of sound in mercury [34], an important parameter in the operation of the ultrasonic manometers discussed below. This experiment also employed a chain suspension to minimize surface vibrations, but in place of fringe counting it used an exact-fractions technique, referenced below, to effectively eliminate loss-of-signal problems associated with reflections from a disturbed surface. Measurements of height changes between 50 mm and 400 mm were made with an imprecision of 0,04 µm, and the overall uncertainty in the apparent speed of sound was equivalent to a standard deviation of 1,4 ppm. This technique is the most direct way to make a high-accuracy measurement of the displaced height, but it is also one of the more difficult techniques to use because of the residual vibration problems.

4.3 Ultrasonic detection and measurement

The concept of using long-wavelength radiation to minimize the effects of surface disturbances can be extended further with the use of ultrasound. Ultrasound, generated by a transducer at the bottom of a mercury column, travels up through the mercury, is reflected at the mercury surface and, upon return, is detected at the transducer. A commercial manometer has been produced that uses the transit time of the ultrasound pulse as a measure of the column length. The precision of this technique is limited by the rise time of the ultrasonic pulse, which makes it difficult to determine the arrival time of the return pulse. Heydemann [35] improved upon the time-of-flight technique by transmitting a packet of 100 to 200 sine waves and measuring the phase of the returned signal. This technique minimizes the effects of waveform distortion and the long wavelength, about 150 µm, makes it relatively insensitive to surface disturbances. In spite of the long wavelength, very good length precision can be obtained by making a high-resolution measurement of the phase change. This requires corrections for small errors common to both ultrasound phase meters and optical interferometers [36]; the result is that the height of a 100 mm long mercury column can be routinely determined with an imprecision of 0,02 µm, without any vibration isolation other than a solid floor. This technique, involving the "interference" of two rf signals corresponding to the transmitted and received ultrasonic signals, has been used in the construction of a series of Ultrasonic Interferometer Manometers (UIMs). These manometers, originally described in [13], have fullscale ranges from 13 kPa to 360 kPa.

A second major advantage of ultrasonic techniques is that multiple-wavelength or exact-fractions techniques can be used to measure height changes without fringe counting. The generation of different ultrasound wavelengths requires nothing more than the programming of a high-accuracy rf synthesizer, which allows the easy use of an exact-fraction algorithm [37] to determine the mercury-column height changes. This effectively eliminates the problems of signal interruption and permits rapid pressure changes and routine operation without special vibration control, although the 360 kPa UIMs do require a very stable base for fullscale operation. Although the pressure can be changed with arbitrary speed, time must still be allowed for thermal equilibrium after a large change. The measurements are automated and pressure changes can be followed with a measurement every 30 seconds. These advantages are offset by several disadvantages relative to optical interferometry. While the frequency of the ultrasound is well known, the accuracy of the ultrasonic wavelength depends on the uncertainty of the speed of sound. Further, diffraction corrections, which are negligible in most optical interferometers, can be as large as 6 ppm to 8 ppm. The most significant disadvantage is the relatively large temperature coefficient of the speed of sound, which effectively triples the temperature coefficient of the manometer, compared with the temperature dependence of the mercury density alone. The pressure coefficient is also larger than the compressibility of mercury alone, but it still requires only a small correction for most measurements. However, as noted above, the speed of sound has been determined with an uncertainty of 1,4 ppm, and since the ultrasonic technique is fully automated it does not require servo systems, mechanical access or operator intervention, so that good temperature uniformity and stability are more easily achieved, and an accurate measurement of the mercury temperature is relatively easy. The current design uses passive temperature control; the manometer is surrounded by a 5 cm thick aluminium shell and expanded-foam thermal insulation. This permits the routine operation of these instruments in a normal laboratory environment with a total uncertainty characterized by a standard deviation of 0,009 Pa and 2,6 ppm of the pressure. Improved imprecision can be obtained at pressures below 100 Pa.

5. General Comments

The primary option available to the designer of a high-accuracy manometer is the choice of a technique to locate the mercury surface and measure its height. For state-of-the-art manometers accuracy is obviously a factor. However, for general-purpose pressure standards, flexibility and ease of use are also important considerations, and cost generally cannot be ignored. Further, the length detection and measurement technique must accommodate the maintenance of a uniform and stable mercury temperature. The white-light-fringe technique requires manual or servo adjustment of a tracking mirror which limits its ease of use and the ability to follow changing pressures. It also requires, in most instruments, a significant correction for the index of refraction of air. However, its use is well-established in several laboratories and the uncertainties have been thoroughly documented. The capacitance-detection and cistern technique is very difficult to use in its most accurate implementation, while the commercial implementation is very easy to use, but does not achieve state-of-the-art accuracy. However, modifications of the commercial instruments can significantly improve their accuracy while still maintaining reasonable flexibility of use. The precision of the float and optical interferometry technique is limited by capillary effects, but with care a precision can be achieved that is adequate for state-of-the-art measurement of atmospheric pressures. Further, it is easy to use and can follow changing pressures. Optical interferometry used directly with the mercury surface is the most accurate technique available and allows for the measurement of changing pressures, but is difficult to implement. The ultrasonic technique is easy to use and achieves very good imprecision, which is somewhat surprising considering that it uses much longer wavelengths (150 µm) than the optical interferometers. While its total uncertainty is competitive with other techniques, further improvements will be limited by the large temperature coefficient and the uncertainty in corrections for diffraction effects. In all cases, it should be kept in mind that determining the temperature of the mercury is a significant problem, and that speed of operation will ultimately be limited by temperature gradients, thermal inertia and adiabatic heating effects.

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References

1. Guildner L. A., Terrien J., *Mercury Absolute Manometers*, In *Experimental Thermodynamics*, Vol. II, Part 1 (Edited by B. Leneindre and B. Vodar), London, Butterworths, 1975, Chap. 4, 115-132.
2. Ruthberg S., Pressure Measurements for the Range 1 kPa to 100 µPa, In *Experimental Thermodynamics*, Vol. II, Part 6 (Edited by B. Leneindre and B. Vodar), London, Butterworths, 1975, Chap. 4, 229-272.
3. Peggs G. N., A Review of the Fundamental Methods for Measuring Gauge Pressures up to 1 kPa, *J. Phys. E.*, 1980, **13**, 1254-1262.
4. Pavese F., Molinar G. F., Modern Gas Based Temperature and Pressure Measurements, In *International Cryogenic Monograph Series* (Edited by K. D. Timmerhaus, A. F. Clark and C. Rizzuto), New York, Plenum, 1992.
5. Tilford C. R., Pressure and Vacuum Measurements, In *Physical Methods of Chemistry*, Vol. VI (Edited by B. W. Rossiter and R. C. Baetzold), New York, John Wiley and Sons, 1992, Chap. 2.
6. Faller J. E., Marson I., Ballistic Methods of Measuring *g* – the Direct Free-fall and Symmetrical Rise-and-fall Methods Compared, *Metrologia*, 1988, **25**, 49-55.
7. Wilkinson M. C., The Surface Properties of Mercury, *Chem. Rev.*, 1972, **72**, 575-625.
8. Cook A. H., Measurements of the Density of Mercury. II. Content Method, *Philos. Trans. R. Soc. London, Ser. A*, 1961, **254**, 125-154.
9. Adametz H., Wloka M., Measurements of the Absolute Density of Mercury in the ASMW, *Metrologia*, 1991, **28**, 333-337.
10. Sommer K.-D., Poziemski J., Density, Thermal Expansion and Compressibility of Mercury, *Metrologia*, 1993/94, **30**, 665-668.
11. Patterson J. B., Prowse D. B., Comparative Measurement of the Density of Mercury, *Metrologia*, 1985, **21**, 107-113.
12. Beattie J. A., Blaisdell R. E., Kaye J., Gerry H. T., Johnson C. A., An experimental study of the absolute temperature scale. VIII. The thermal expansion and compressibility of vitreous silica and the thermal dilation of mercury, *Proc. Am. Acad. Arts Sci.*, 1941, **74**, 371-388.
13. Heydemann P. L. M., Tilford C. R., Hyland R. W., Ultrasonic Manometers for Low and Medium Vacua under Development at NBS, *J. Vac. Sci. Technol.*, 1977, **14**, 597-605.
14. Blaisdell B. E., The Physical Properties of Fluid Interfaces of Large Radius of Curvature, *J. Math. Phys. (Cambridge, Mass)*, 1940, **19**, 186.
15. Stimson H. F., Precision Resistance Thermometry and Fixed Points, In *Temperature: Its Measurement and Control in Science and Industry*, Vol. II (Edited by Hugh C. Wolfe), New York, Reinhold, 1955, 141.

16. Guildner L. A., Stimson H. F., Edsinger R. E., Anderson R. L., An Accurate Mercury Manometer for the NBS Gas Thermometer, *Metrologia*, 1970, **6**, 1-18.
17. Izrailov K. S., Kirenkov I. K., Capacitance Mercury Manometer for a Gas Thermometer, *Trudy VNIIM*, 1961, **51** **(111)**, 5.
18. Riety P., Lecolliniet P., Le système de réference des pressions de l'Institut National de Metrologie, *Bull. Inf. Bur. Natl. Metrology*, April 1977, **28**, 13-21.
19. Klingenberg G., Ludicke F., Characterization of a Pressure Balance from Dimensional Measurements and from Pressure Comparison Experiments, *PTB-Mitteilungen*, 1991, **101**, 7-18.
20. Jäger J., Use of a Precision Mercury Manometer with Capacitance Sensing of the Menisci, *Metrologia*, 1993/94, **30**, 553-558.
21. Skrovánek T., Lanak D., Keprt A., Novy etalonovy kvapalinovy tlakomer, *Ceskoslovenska standardizance*, 1978, **11**, 442-448.
22. Farár P., Skrovánek T., Faltus Z., Chytil M., The SMU Primary Mercury Manometer and its Comparison with Three Manometers of Different Design, *Metrologia*, 1993/94, **30**, 751-755.
23. Terrien J., Méthodes optiques pour mesurer la hauteur de mercure d'un manomètre; nouveau manomètre interferentiel, *Rev. Opt.*, 1959, **38**, 29.
24. Kaneda R., Sudo S., Nishibata K., An Interferometric Primary Standard Barometer, *Bull. Natl. Res. Lab. Metrology*, 1964, **9**, 24-36.
25. Bonhoure J., Terrien J., The New Standard Manobarometer of the Bureau International des Poids et Mesures, *Metrologia*, 1968, **4**, 59-68.
26. Mitsui K., Sakurai H., Mochizuki T., A gas thermometer measurement below IPTS range, In *Temperature: Its Measurement and Control in Science and Industry*, Vol. 4, Pittsburg, Pa., ISA, 1974, Part 1, Chap. 31, 331-338.
27. Zakharov A. A., Astrov D. N., Belyanskii L. B., Dedikov Yu. A., Polunin S. P., Interference Mercury Manometer, *Prib. Tech. Eksp.*, 1986, **3**, 196-201 (in Russian).
28. Ooiwa A., Ueki M., Kaneda R., New Mercury Interferometric Baromanometer as the Primary Pressure Standard of Japan, *Metrologia*, 1993/94, **30**, 565-570.
29. Bennett S. J., Clapham P. B., Daborn J. E., Simpson D. I., Laser Interferometry Applied to Mercury Surfaces, *J. Phys. E*, 1975, **8**, 25-27.
30. Harrison E. R., Hatt D. J., Prowse D. B., Wilbur-Han J., A New Interferometric Manometer, *Metrologia*, 1976, **12**, 115-112.
31. Alasia F., Capelli A., Cignolo G., Sardi M., A New Generation of Mercury Manometers at the IMGC, *Metrologia*, 1933/94, **30**, 571-577.
32. Yi-tang Sheng, Nui-wen Han, Chun-shan Guo, Ming-bo Duan, Ying-zu Xu, A New Primary Standard Manometer, *Proc. 11th Triennial World Congress of the International Measurementation Confederation (IMEKO): Metrology*, Houston, TX, October 1988, 265-270.
33. Tilford C. R., A Fringe Counting Laser Interferometer Manometer, *Rev. Sci. Instrum.*, 1973, **44**, 180-182.
34. Tilford C. R., The Speed of Sound in a Mercury Ultrasonic Interferometer Manometer, *Metrologia*, **24**, 1987, 121-131.
35. Heydemann P. L. M., A Fringe Counting Pulsed Ultrasonic Interferometer, *Rev. Sci. Instrum.*, 1971, **42**, 983-986.
36. Heydemann P. L. M., Determination and Correction of Quadrature Fringe Measurement Errors in Interferometers, *Appl. Opt.*, 1981, **20**, 3382-3384.
37. Tilford C. R., Analytical Procedure for Determining Lengths from Fractional Fringes, *Appl. Opt.*, 1977, **16**, 1857-1860.